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DAM OF THE KOLYMA HYDROELECTRIC POWER PLANT (PLOTINA KOLYMSKOI --ETC(U)  
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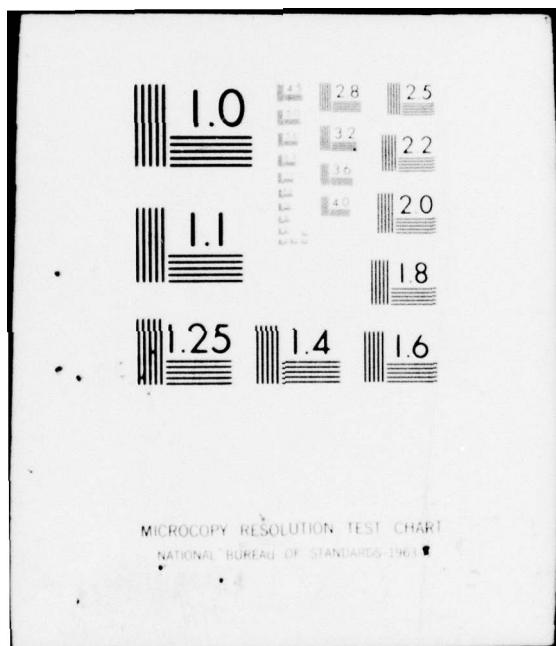
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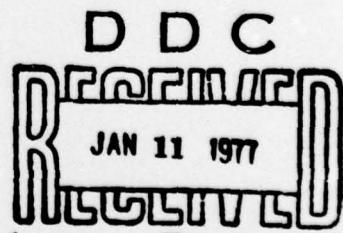
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~~DAM OF THE~~  
~~KOLYMA HYDROELECTRIC POWER PLANT.~~

V.G. Petrov and E.D. Losev



CORPS OF ENGINEERS, U.S. ARMY  
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY  
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## THE DAM OF THE KOLYMA HYDROELECTRIC POWER PLANT

V.G. Petrov and E.D. Losev

The site of the Kolyma Hydroelectric Power Plant is located in the upper course of the Kolyma River. The natural conditions of the region of construction are extremely difficult. The climate is extremely severe (mean annual temperature -12 C), summer is short, continuous permafrost, heavy spring floods in a narrow channel, far from developed regions of the country -- this is a far from complete list of the conditions which complicated the planning and construction of the Kolyma Hydroelectric Power Plant.

Technical and economic comparison of various versions of arrangement of the power plant with various types of dams showed that there were significant advantages to the construction of the dam from locally available materials. The cost of the entire power plant with a stone-earthen dam would be 15% less, the cost of the initial construction complex -- 26% less than the cost of the version with a concrete dam.

Comparison of versions resulted in the acceptance of the following arrangement of the hydraulic power unit in the technical plan. The bed of the Kolyma River would be dammed with a rock-fill dam with a core of cohesive soil. The operational spillway and power plant unit would be constructed on the left bank. The spillway, equipped with 6 segmented gates, each with a head of 20 m and a span of 17 m, is terminated in a chute and lip.

The water intake of the power plant is constructed on the right side of the approach channel of the spillway. The penstocks connect the water intake to the subterranean power plant. The structures of the power plant unit (control building, distributing devices and supplementary areas) are placed along the left bank of the river.

A construction spillway consisting of trenches in rock covered with a reinforced concrete arch is constructed on a terrace on the right bank to pass the construction flow and the flow during the period of temporary operation. The trench is lined with concrete and equipped with a regulating head.

The dam can be constructed of local material because the region of the site has deposits of all the necessary soil types: granite, loam, various natural sand-gravel mixtures.

The selection of a type of filtration device for the dam was undertaken in two directions:

-- Selection of the placement of the impervious element (screen or core, screen or diaphragm);

-- Selection of the material for the impervious element.

Planning practice shows that the upstream slope of a dam with a core can be made steeper than that of a dam with a screen; due to this, approximately 20% fill volume is saved. The volume of work involved in constructing the core (diaphragm) is also less than the volume of work involved in constructing a screen. These considerations basically determined the selection of a dam with a central antifiltration impervious element.

The selection of a material for the antifiltration device was based on the comparison of dam versions with a soil core and diaphragms of asphalt-concrete, polyethylene film and metal. Economic comparisons showed that all the versions considered would cost the same, within 3-4%.

Calculations and analysis of accumulated experience and investigations showed that the antifiltration properties of materials other than soils are significantly less reliable than a core of soil material, and that their construction requires considerably more manual labor.

These statements are confirmed by world dam construction practice. A general idea of the trends in construction of high dams of local materials is provided by the table below.

TABLE\*

Type of Antifiltration Device	Number of Dams in Height Ranges		
	Over 100 m	100-80 m	80-50 m
Soil core	35 (9)	47 (2)	61 (1)
Soil screen	7 (2)	14 (1)	22 (3)
Reinforced concrete screen	2 (--)	6 (2)	17 (--)
Asphalt-concrete screen	--	--	8 (1)
Steel screen	--	--	2 (--)
Screen of polymer film with loam	--	--	1 (1)
Reinforced concrete diaphragm	--	--	1 (1)
Steel diaphragm	--	--	1 (1)

Note. Parentheses show number of dams constructed under severe climatic conditions.

\*Composed from materials collected by V. G. Radchenko and V. A. Zanrova in Kamenno-Zemlyanye i Kamennonabrosnyye Plotiny, 1971.

Based on a comparison of the entire range of problems (economics, technology, reliability in operation) for the Kolyma Hydroelectric Power Plant, a dam of rock fill with a soil core was selected. The design of the version of the dam selected is shown in Figure 1.

The height of the dam is 126.0 m, length along the top 759 m, length at the base 370 m.

In order to decrease crack formation in the core and considering the general arrangement of structures, the dam was given a curved outline in

plan, convex in the upstream direction. The radius of the axis of the dam is 1000 m except for the left bank attachment, where the radius is decreased to 200 m due to the conditions of arrangement of construction elements.

The supporting prisms of the dam consist of rock fill, almost entirely obtained from useful mine operations. Particular attention was required by the question of placement of the rock mass in the dam. Rock fill for high dams is usually artificially compacted, though the need for this requirement is somewhat doubtful.

We know that artificial compacting has practically no influence on the angle of internal friction in a fill and, therefore, does not allow the profile of the dam to be compressed or the stability of its slopes to be increased. The need for compacting can be based only upon a desire to decrease settling of the supporting prisms. However, the influence of settling of filled prisms on the reliability of the dam may even be positive. For example, if settling of the prisms is greater than the settling of the core, the prisms "hang" on the core, compressing it and preventing the development of dangerous horizontal cracks in the core. In the case of well compacted prisms, in contrast, the core, should it settle, will experience tensile stresses through its horizontal sections ("hang" on the prisms) and horizontal cracks may develop clear through the upper portion of the core.

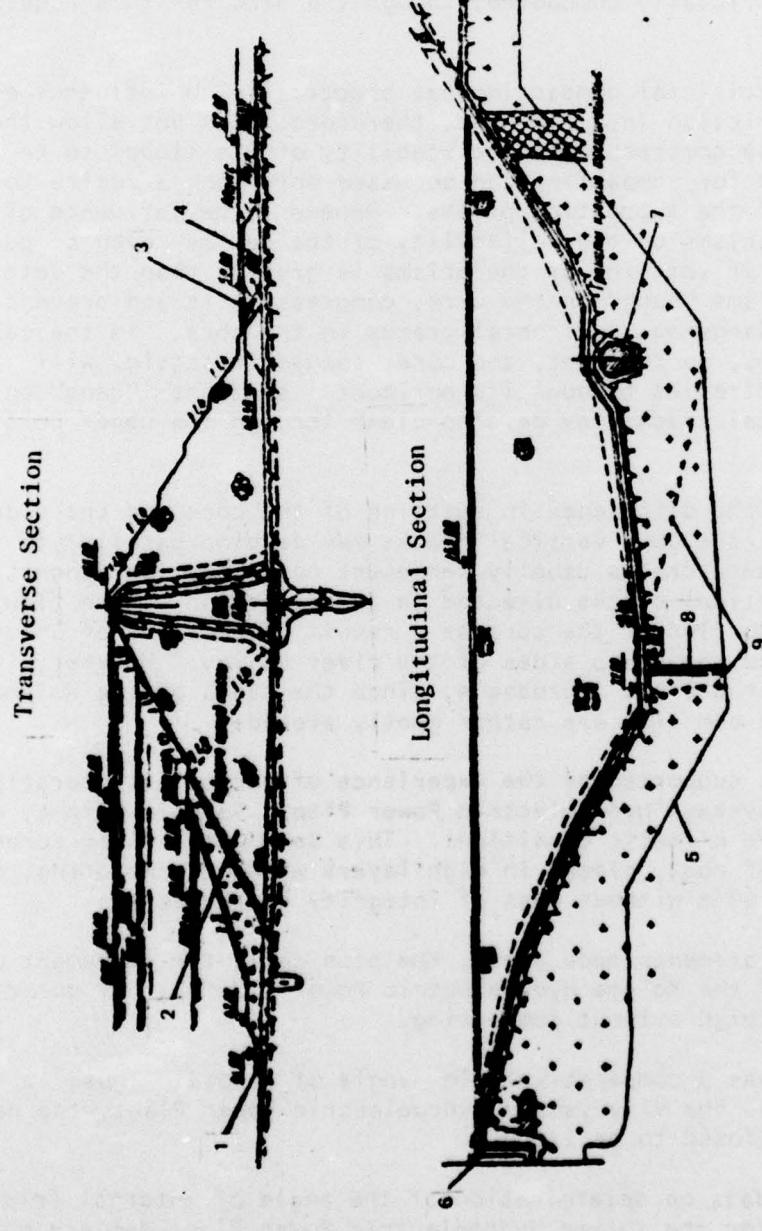
As a result of the difference in settling of the core and the side prisms at the top of the dam, vertical cracks may develop parallel to the axis of the dam. These cracks usually represent no filtration danger. Furthermore, the vertical cracks directed in the direction of the flow may arise in the upper portion of the core as a result of settling of uncompacted prisms next to the steep sides of the river valley. However, in the present case these cracks are improbable, since the banks of the Kolyma in the region of the dam site are rather gently sloped.

These facts are supported by the experience of successful operation of the dam of the Vilyuyskaya Hydroelectric Power Plant, 75 m in height, constructed under severe climatic conditions. This dam, with a loam screen and a supporting prism of rock, placed in high layers without compacting, operates with a head of 60 m without loss of integrity of the screen.

Based on the statements made above, the plan calls for placement of supporting prisms of the Kolyma Hydroelectric Power Plant Dam of unsorted rock in layers 10 m high without compacting.

Unsorted rock has a comparatively low angle of repose. Thus, in experimental fills at the Vilyuyskaya Hydroelectric Power Plant, the natural angle of repose was found to be 1:1.4.

Observational data on determination of the angle of internal friction of the quarry mass for the Kolyma Hydroelectric Power Plant dam are not as yet available. Averaging data from 30 foreign and Soviet dams over 80 m in height yields an angle of internal friction of the fill (with a reserve factor of 1.3) of about 37°. For the Kolyma Hydroelectric Power Plant, we



**Figure 1.** Dam of Kolyma Hydroelectric Power Plant. 1, Upstream Low Water Blanket; 2, Temporary Dam; 3, Downstream Blanket; 4, Rocky Soil Blanket; 5, Boundary of Deep Cementation; 6, Water Intake; 7, Temporary Water Passage Tube; 8, Deep Cementation Borehole; 9, Boundaries of Thaw Area in Bed

must also consider the following factors. Under the severe climatic conditions of the region, during the process of air exchange in the pore of the downstream prism in summer, moisture condenses from the air in the cold fill. This forms ice within the pores, which may reduce the coefficient of internal friction of the material. Until reliable data are produced by the required investigations of the process of moisture condensation, the behavior and mechanical properties of the fill with internal ice, it would be desirable to reduce the design mean internal friction angle somewhat.

Another factor influencing the assignment of calculation parameters is the use as a material in the supporting prisms of unsorted quarry mass.

In foreign practice, it is almost universal, and in domestic practice it is widespread, to sort out the fines from quarry mass before placement, as they reduce the angle of internal friction, and also the large stones, which prevent compacting of relatively thin fill layers. This processing not only increases the cost of fill, but also decreases the yield of usable material from the quarry. These factors reduce the economic effect achieved by decreasing the volume of fill by the use of steeper slopes to naught (this savings amounts to 5-10% of the fill volume). It is therefore considered expedient to use unsorted quarry mass as the material for the supporting prisms of the Kolyma dam.

All of these factors have served as a basis in the present stage, before the performance of field testing, for assigning a design angle of internal friction of the quarry mass of 35°.

The core of gravelly loam is placed symmetrically relative to the axis of the dam.

The head gradient in cores of loam for high dams is usually assigned between 2.0 and 3.5, though certain laboratory investigations have indicated the possibility of significantly higher gradients. Under the conditions of the Kolyma power plant, where some of the loam in the core will be placed in winter and the probability of production defects is significantly higher than in ordinary construction practice, the maximum gradient is limited to 3.0. Considering that the weakest spot from the standpoint of filtration is the contact between the core and the base, the bottom of the core is spread so that the maximum head gradient along the line of contact between core and base is not over 2.5.

Two neighboring deposits of loam (Nos. 3 and 17) suitable for the construction of the core of the dam have been found 6 km from the construction site. The loam in both these deposits is gravelly, with inclusions of large lump material. The averaged curve of the granulometric composition of deposit No. 3 is presented in Figure 2. The loam of this deposit contains 60-72% fines (fraction smaller than 2 mm), while the soil of deposit No. 17 contains 50-80% fines.

As a result of experiments performed at the Leningrad Polytechnical Institute, the following characteristics of the loam were produced: filtration factor  $A \times 10^{-6}$  cm/sec, angle of internal friction 22°, cohesiveness

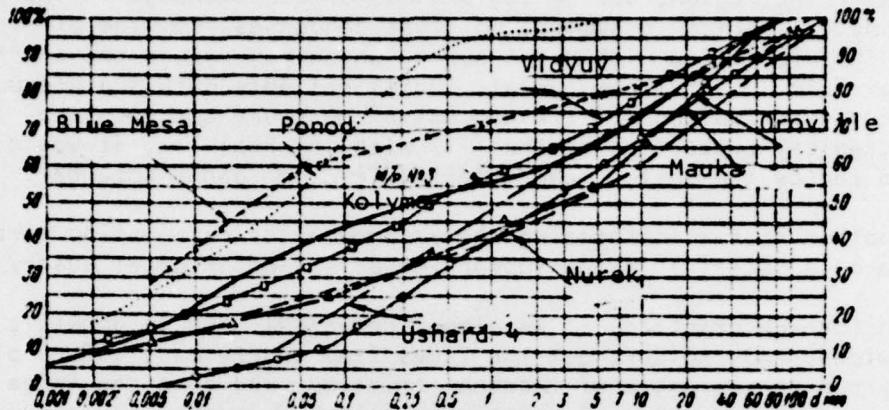


Figure 2. Averaged Granulometric Curve of Loams of Deposit No. 3

$0.1 \text{ kg/cm}^2$ . Experiments involving shear of frozen loam with thawed loam yielded the same results. The compression curve is presented in Figure 3. As a result of studies, the control density of the fines in the core is assigned as at least  $1.65 \text{ t/m}^3$ , corresponding to a volumetric weight of the loam of  $1.98 \text{ t/m}^3$ .

The upper layers of the core are not subjected to sufficient self-compression; therefore, the control density of the fines in the upper 10 m of the core is increased to  $1.75 \text{ t/m}^3$  (for loam --  $2.05 \text{ t/m}^3$ ).

The loams in the deposits are in a plastic frozen state and can be extracted by the technology developed for construction of the Vilyuyskaya Power Plant. In summer, the thawed layers of loam are scraped up with bulldozers into rows 3-5 m high, which lose most of their excess moisture in a few days. The loam is then placed in large piles, where it is stored until the required moisture content is reached. In the winter, the surface of the piles is salted and covered. As each pile is worked by excavator, the material is mixed and its composition averaged. The loam is placed in the core in layers 30-40 cm thick and rolled by trucks.

The transition zones in the dam are to be made of a sandy-gravelly soil from various layers of deposit No. 14, which has the necessary granulometric composition.

The Kolyma Power Plant will be constructed with an increasing shortage in power capacity of the power system. Therefore, the decision has been made to put the power plant in operation at an intermediate head created by the upstream "barrier" 60 m high. This barrier should be almost completely constructed in a single season between floods -- from October through May. The antifiltration element of the barrier cannot be made using cohesive soil in a single winter. Therefore, the upstream barrier is planned in two

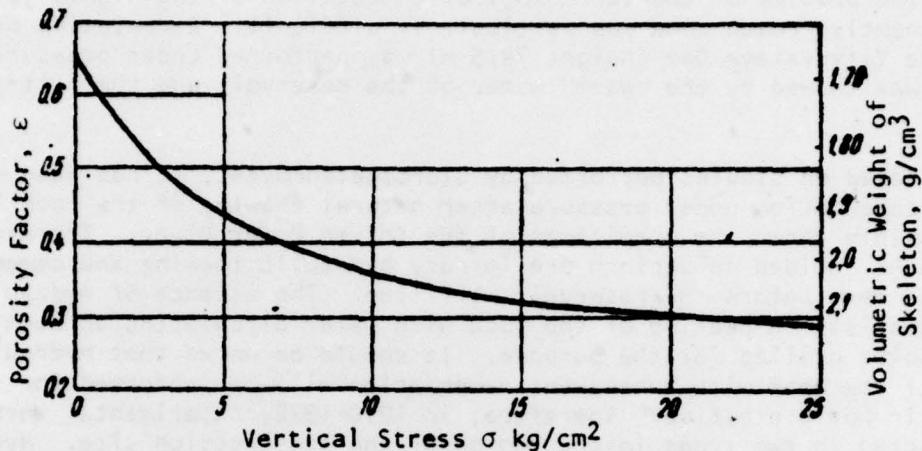


Figure 3. Compression Curve of Loam of Deposit No. 3

versions: with a screen on noncohesive soil and with a diaphragm of polyethylene film. In the first of these versions, the screen is placed using sandy-gravelly soil from deposit No. 15, which has a filtration factor on the order of 10 m/day. The head gradient at the screen will not exceed 2.0. The diaphragm in the second version is constructed of three layers of polyethylene film.

Work on improvement of the plan for the upper barrier is continuing. Regardless of which version is used in construction, creation of the startup head with the upper barrier will allow the first power units to be put on stream three to four years earlier and reduce the capital investments required in the startup power plant complex by up to 45% of the total cost of the complex.

Particular attention has been given to development of the method of mating the dam with the base. The bedrock in the region of the construction site consists of strong, jointed granite. In the stream bed, the granite is covered with a layer of alluvium of variable grain size 1-2 m thick, on the banks -- by deluvium up to 3-5 m thick on the left bank and 20-30 m thick on the right bank. The deluvium has low internal friction and significant settling capacity upon thawing. The upper layer of granite (unloading zone) is distinguished by its significant permeability (filtration factor up to 40 m/day).

The layer of deluvium beneath the bank portions of the dam must be removed, since it greatly reduces the stability of the supporting prisms. The alluvium in the stream bed beneath the supporting prisms will be retained.

The core of the dam will contact the bedrock through a deep, two-row cementation curtain with a maximum depth of 65 m. The bedrock beneath the core and the transition zones will be smoothed by a concrete facing 0.5 m thick and strengthened by the area of cementation.

The problem of the technology of cementation of the highly jointed permanently frozen rock was particularly difficult. Cementation of the base of the Vilyuyskaya Dam (height 74.5 m) was performed under pressure as the rock was thawed by the "warm" water of the reservoir and the filtration flow.

Based on studies performed by Gidrospetsproyekt, it has been concluded that cementation under pressure after natural thawing of the rock is impossible under the conditions of the Kolyma Power Plant. Therefore, it has been decided to perform preliminary hydraulic thawing and cementation of the base before the reservoir is filled. The essence of hydraulic thawing consists in heating of the rock with water circulating through special boreholes drilled for the purpose. It should be noted that hydraulic thawing of the rock with subsequent cementation will be performed for the first time in world practice. Therefore, in 1970-1972, experimental work was conducted in two areas in the region of the construction site. Hydraulic thawing boreholes 151-131 mm in diameter and 40-60 m deep were drilled in checkerboard order at a distance of 7 m from each other. Thawing was successfully performed using river water without additional heating. Work on cementation with hydraulic thawing does not depend on the uncontrolled process of natural thawing and is not made more difficult by the filtration of water under pressure. Therefore, the cost of associated operations and repeated cementation should be reduced in comparison with the Vilyuyskaya technology, which in our opinion should compensate to some extent for the additional cost of artificial thawing of the rock.

Work on other versions of antifiltration curtains in the base (frozen curtain, drilled concrete wall, etc.) has shown that cementation with hydraulic thawing is the most economical method.

Hydraulic thawing and cementation of the base beneath the core will be performed from a gallery 3.5 m wide and 4 m high. On the left bank, the gallery is connected with the cementation bed of the power plant intake, on the right bank -- with the tunnel from which cementation of the bank adjacent to the dam will be conducted.

The placement of the slopes of the dam was determined by calculation of shear stability using circular-cylindrical surfaces. The most dangerous case for wetted slopes was found to be the case of an intermediate water level (water wetting approximately 40% of the height of the slope). The critical slipping surfaces pass almost entirely through the rock fill. The mean placements determined by calculation are equal for the wet slope (upper and lower portion of the downstream slope) as 1:1.95, for the dry slope -- 1:1.85, the stability reserve factor in this case being the normal 1.3.

Calculations of the flat slipping surfaces yielded higher stability reserves. The beddings of the slopes used provide stability of the dam with a seismic shock of up to 8 units [scale not stated -- tr.].

The stress state of the dam was calculated by the method of "finite elements" at VODGE0. The necessary physical and mechanical characteristics of the elements of the dam in this case were determined by laboratory experiments, as a function of the stress state, and in this form were entered into the calculation. This solution of the nonlinear problem of the theory of elasticity did not change the overall evaluation of the stability of the slopes of the dam.

Significant work on determination of the temperature mode of the dam was performed in the scientific research section of Lengidroproyekt. Calculations on an electric integrator considered the transfer of heat by the filtering water and approximately considered the influence of air convection in the downstream wedge of the dam. The studies showed that two main temperature zones are formed in the downstream wedge of the dam:

- From the top to half-height of the dam -- an area of temperature which varies during the year;
- From half-height of the dam to the downstream water level -- an area of constant below-freezing temperature; ice will form in the cavities in the fill in this area.

Nevertheless, the core of the dam, if it is not entirely frozen in the process of construction (which is excluded by the planned rate of construction), will be thawed due to the influence of the filtration flow.

In order to observe settling, filtration, pore pressure in the core, the stress state and temperature mode in the dam and base, various instruments are to be installed. The sensors are concentrated in 7 measurement lines perpendicular to the axis of the dam.

Surface marks and reference points will be used for observation by geodetic methods, as well as measurement pipes into the body of the dam with the corresponding inclinometer apparatus. In the region of the power plant, a plan-altitude reference network is being created. Geodetic methods of observation allow the general and layer-by-layer spatial displacements of the body of the dam, displacements and inclinations of concrete structures to be determined.

Filtration through the body of the dam and base will be observed by means of piezometers placed in the measurement lines. It is also possible to use piezodynamometers, designed for the measurement of pore pressure, for this purpose.

To determine stresses in the body of the dam and its base, piezodynamometers, soil dynamometers and dynamometers for the rock fill will be used.

The most important task is the observation of the temperature mode of the dam and its base. In addition to remote thermometers placed in the measurement lines in the rock of the base and the body of the dam, test

measurements of the temperature are possible using other string-type sensors. Data on displacements of the zero isotherm in the water-saturated zones of the dam may be duplicated by instruments measuring stresses. The working plan should include a provision for devices allowing measurement of deformation of the flooded upper wedge of the dam.

In the time remaining before construction of the main structures, work must be performed to refine the physical-mechanical and heat-engineering characteristics of the materials of the dam. Observations of an experimental fill, begun in 1973, and an extensive program of experiments at the construction area on the shear of the rock fill will be of great significance for this. We should also summarize the available experience and perform special studies of the process of freezing of ice in fill pores and its influence on the stability of fill slopes.

It is possible that the results of these studies will allow us to plan a more economical profile for the dam.